New results for Higgs production in association with a jet

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After the euphoria

- Roughly a year ago, the announcement of the Higgs discovery generated great excitement

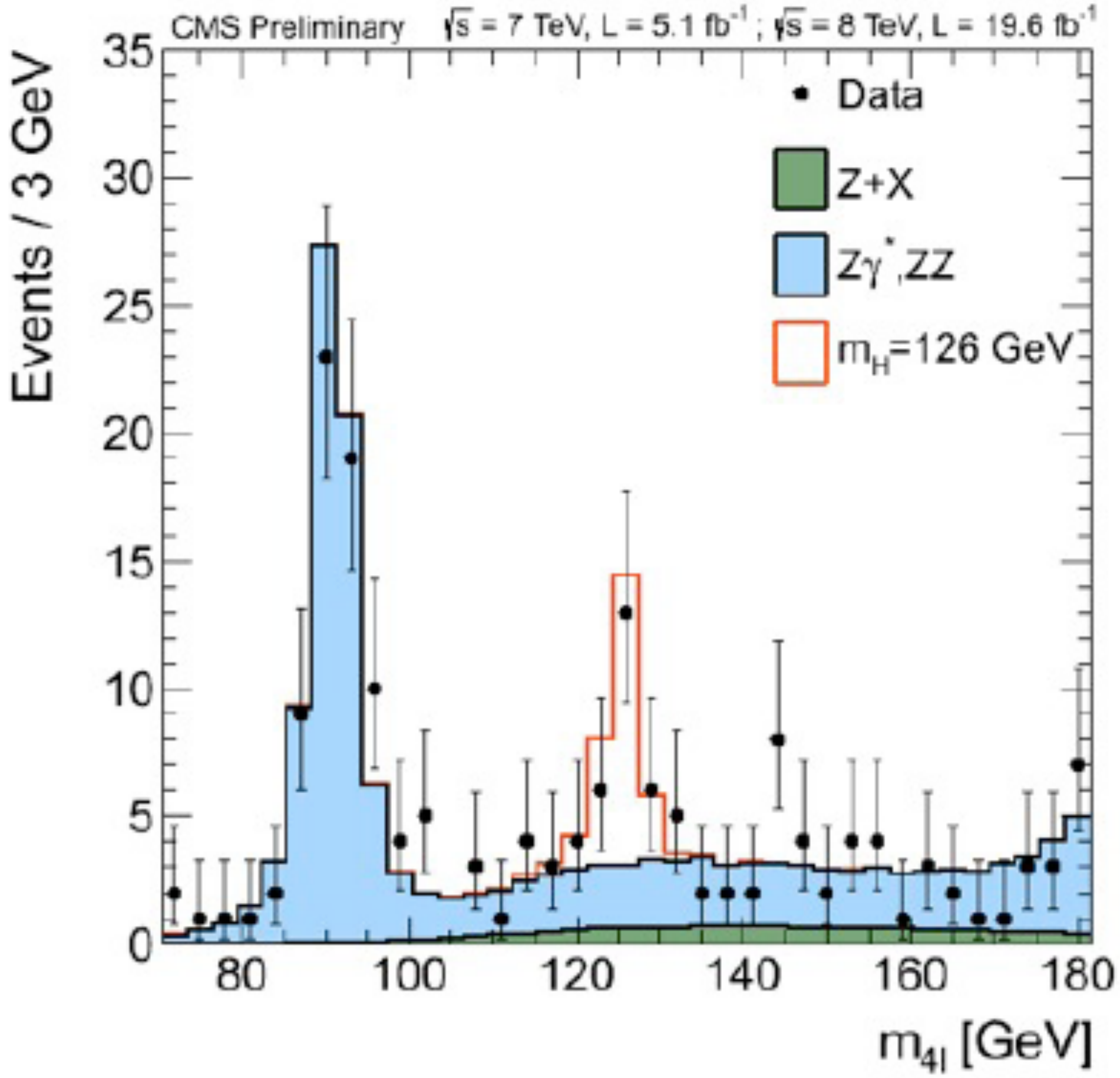
- With the excitement reduced, it’s time to analyze the discovery
- Is it the Standard Model Higgs? Do its couplings deviate?
- Is theory in shape to distinguish between these possibilities?

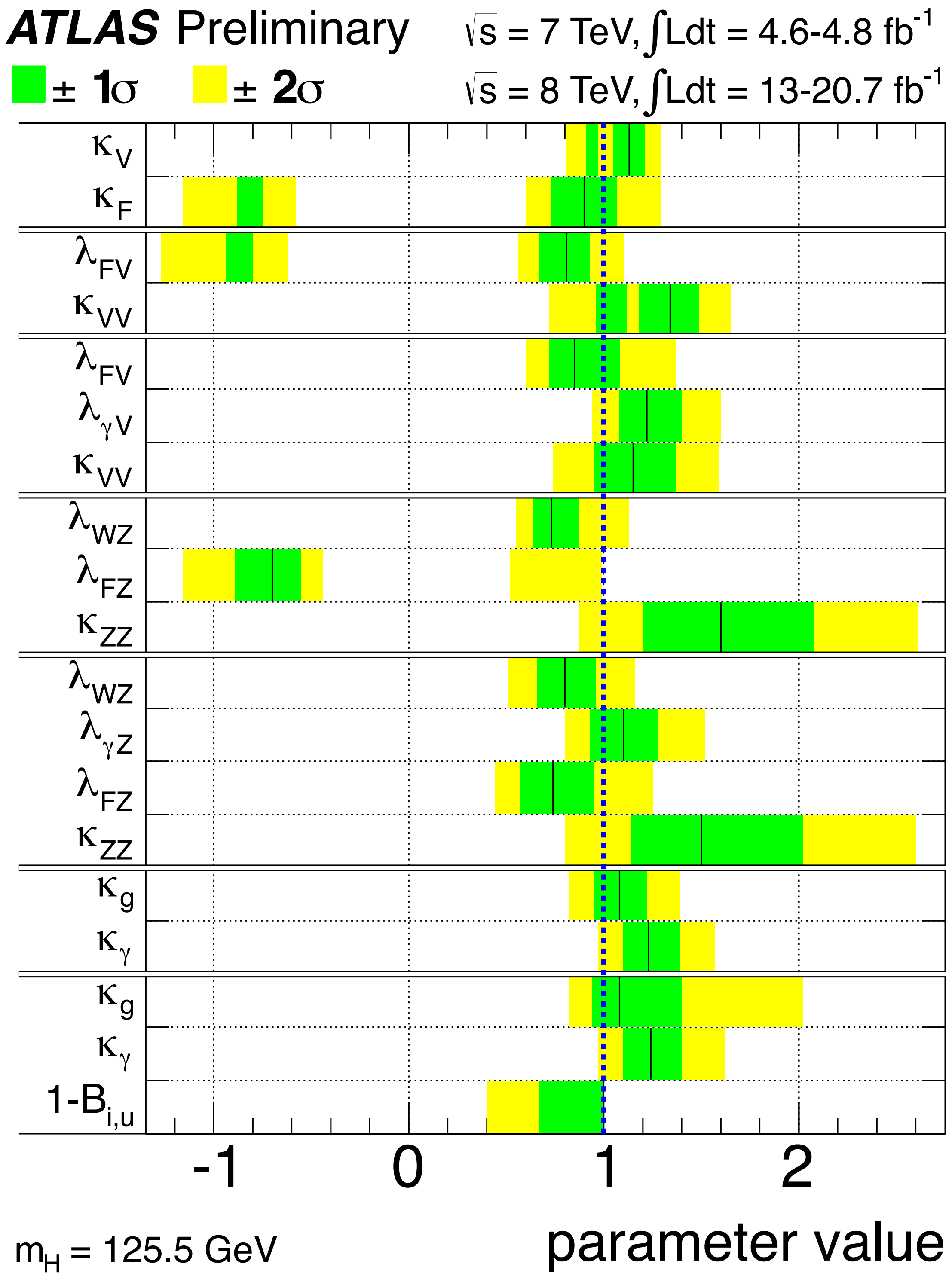
Outline

- Motivation
- Inclusive Higgs production
- H+jet @NNLO in QCD
- Summary

Discovery is the beginning

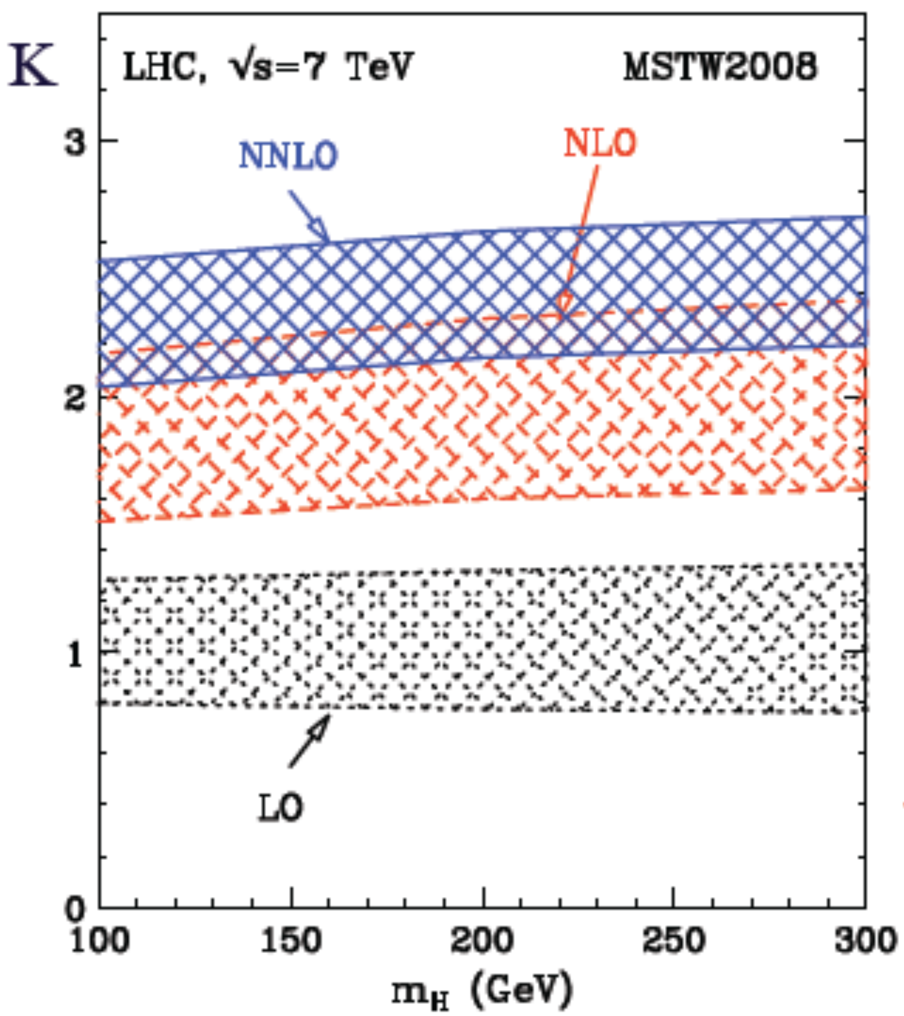
Remarkable progress, from discovery to rapidly sharpening our understanding of this new state





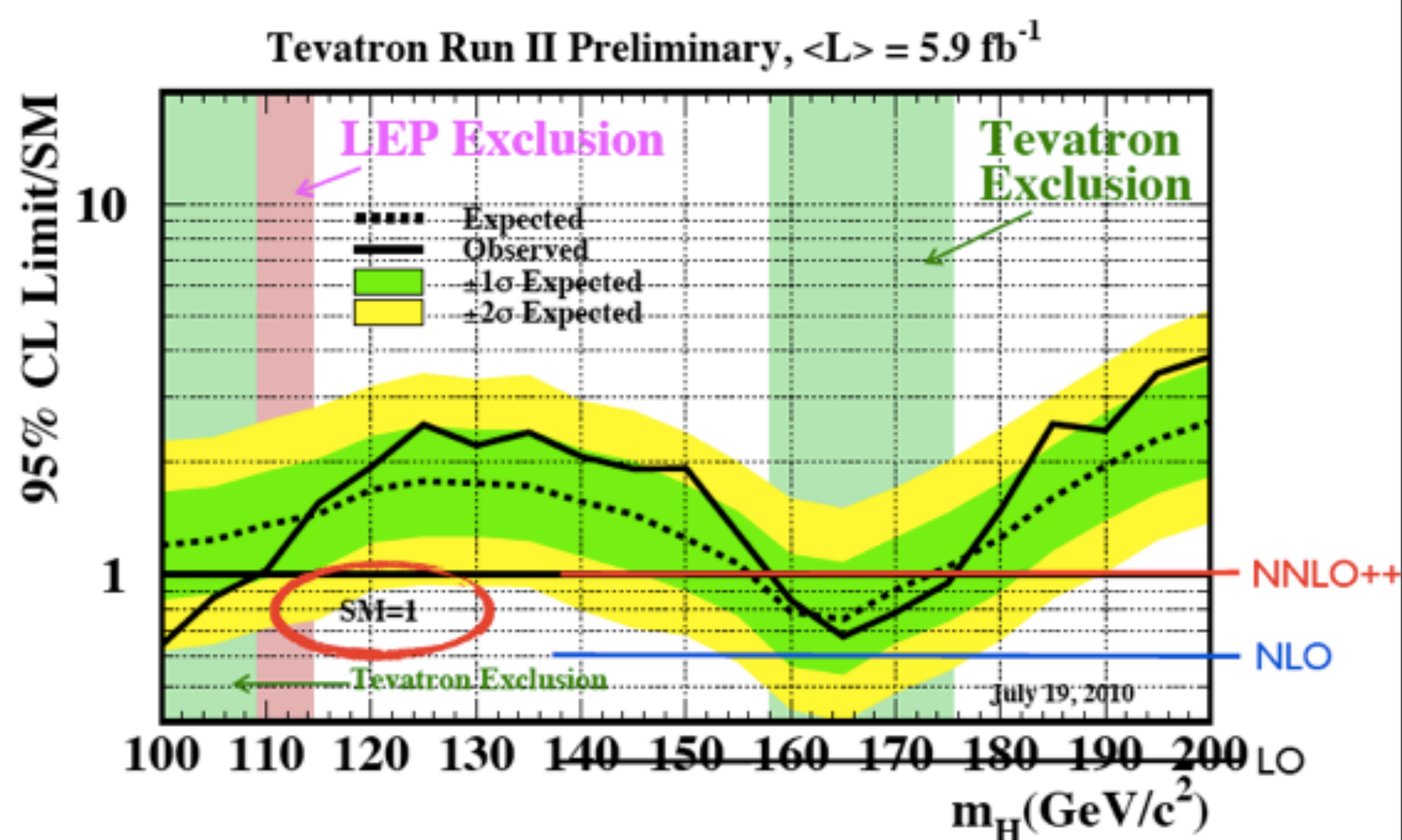
Role of theory

- Precision SM theory played a crucial role in the hunt for the Higgs boson



Higgs predictions receive famously large perturbative corrections

Harlander, Kilgore; Anastasiou, Melnikov; Ravindran, Smith, van Neerven 2002-2003

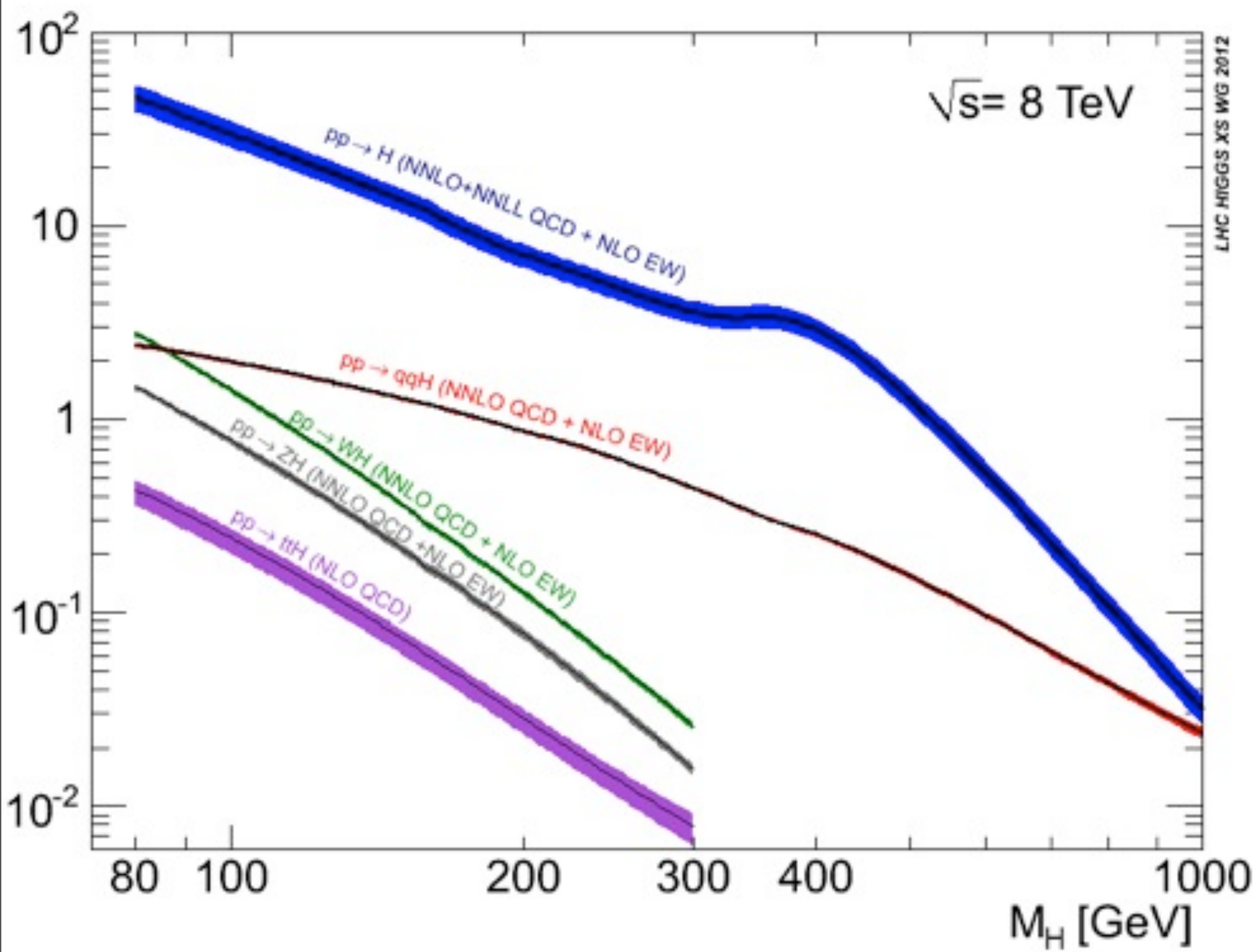


Without NNLO predictions, wouldn't have even realized we were probing the SM Higgs at the Tevatron!

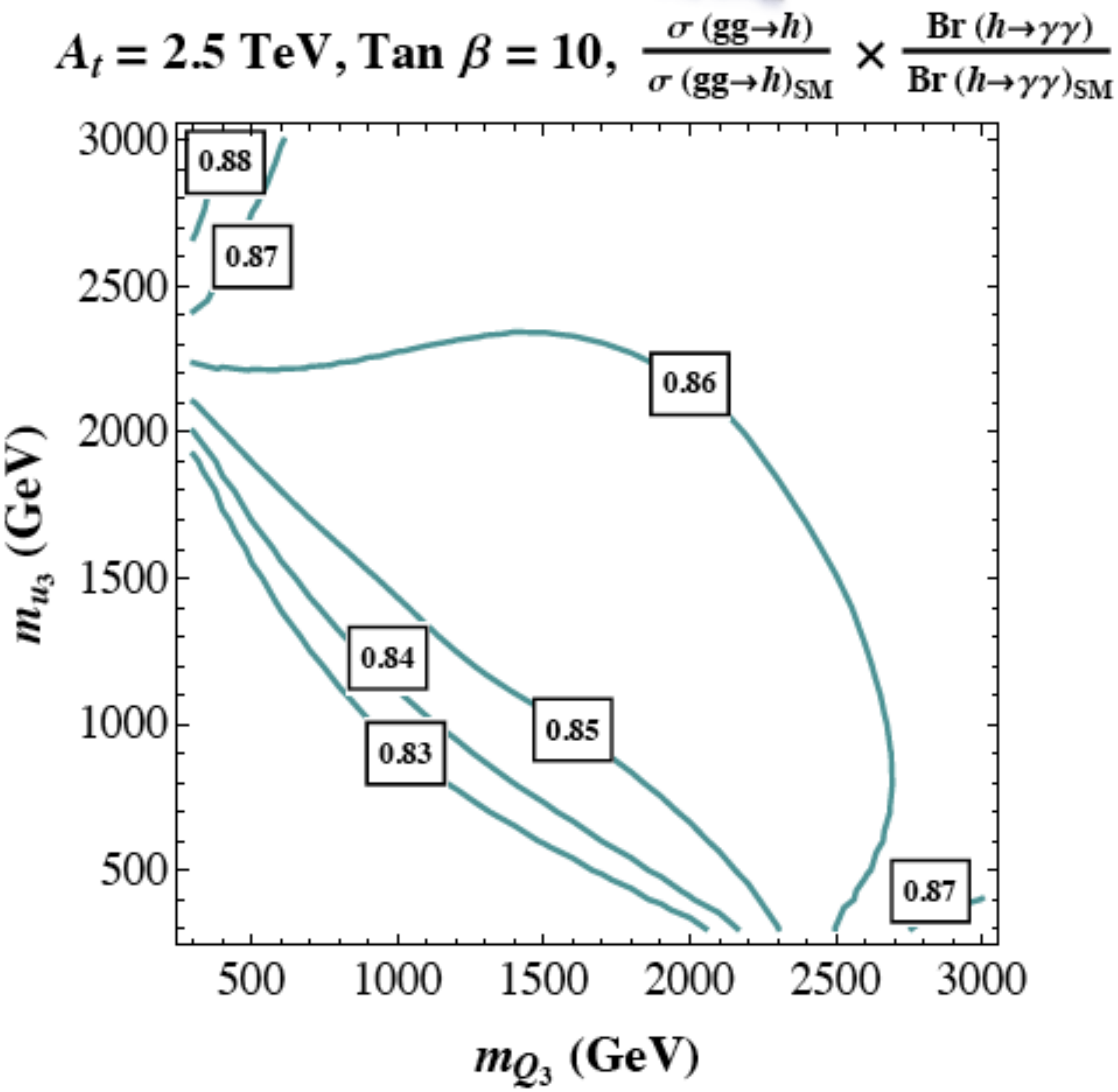
Harlander

First three years of the LHC, Mainz, 2013

Continued importance of precision theory



LHC Higgs cross section working group



Carena, Gori, Shah, Wagner 2011

Small deviations from SM predictions may be a crucial window into physics beyond the Standard Model

Much work done for the total cross section

- Effects of soft-gluon resummation at Next-to-next-to leading logarithmic (NNLL) accuracy (about 6-15%)

  Catani, De Florian, Nason, Grazzini (2003)

- Partial N^{3}LO corrections (soft gluon approximation)

  Moch, Vogt (2005)
  Anastasiou, Duhr, Dulat, Mistlberger (2013)

- Approximate N^{3}LO in QCD by matching two limits: soft gluons and highly energetic gluons

  Ball, Bonvini, Forte, Marzani, Ridolfi (2013)

- Resummation of π^2 factors through appropriate matching condition

  Ahrens, Becher, Neubert, Yang (2008)

- Two-loop EW corrections are also known (effect is about O(5%))

  Aglietti et al. (2004)
  Degrassi, Maltoni (2004)
  Passarino et al. (2008)

- Mixed QCD-EW effects evaluated in EFT approach

  Anastasiou, R.B., Petriello (2008)

- EW effects for real radiation

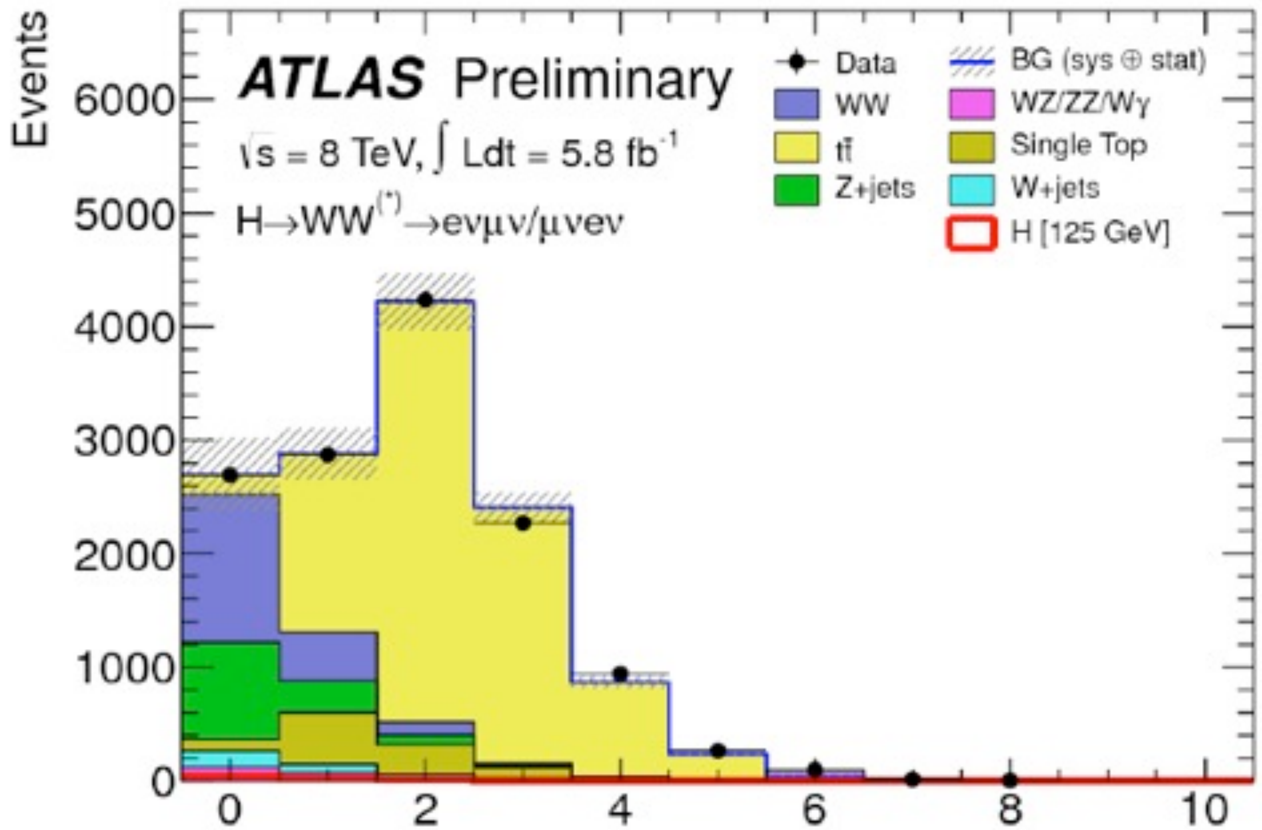
  Keung, Petriello (2009);
  O. Brein (2010)

Higgs in association with jets

- Higgs cross-sections in pp→H→WW are binned according to the jet multiplicity to beat the background

- The measured value of pp→H→WW production cross section results from combining 0 jet, 1 jet and 2 jet cross sections. Each of them has its own uncertainty

- What we knew so far: H+0j @ NNLO, H+1j and H+2j @ NLO



More work needed for differential production

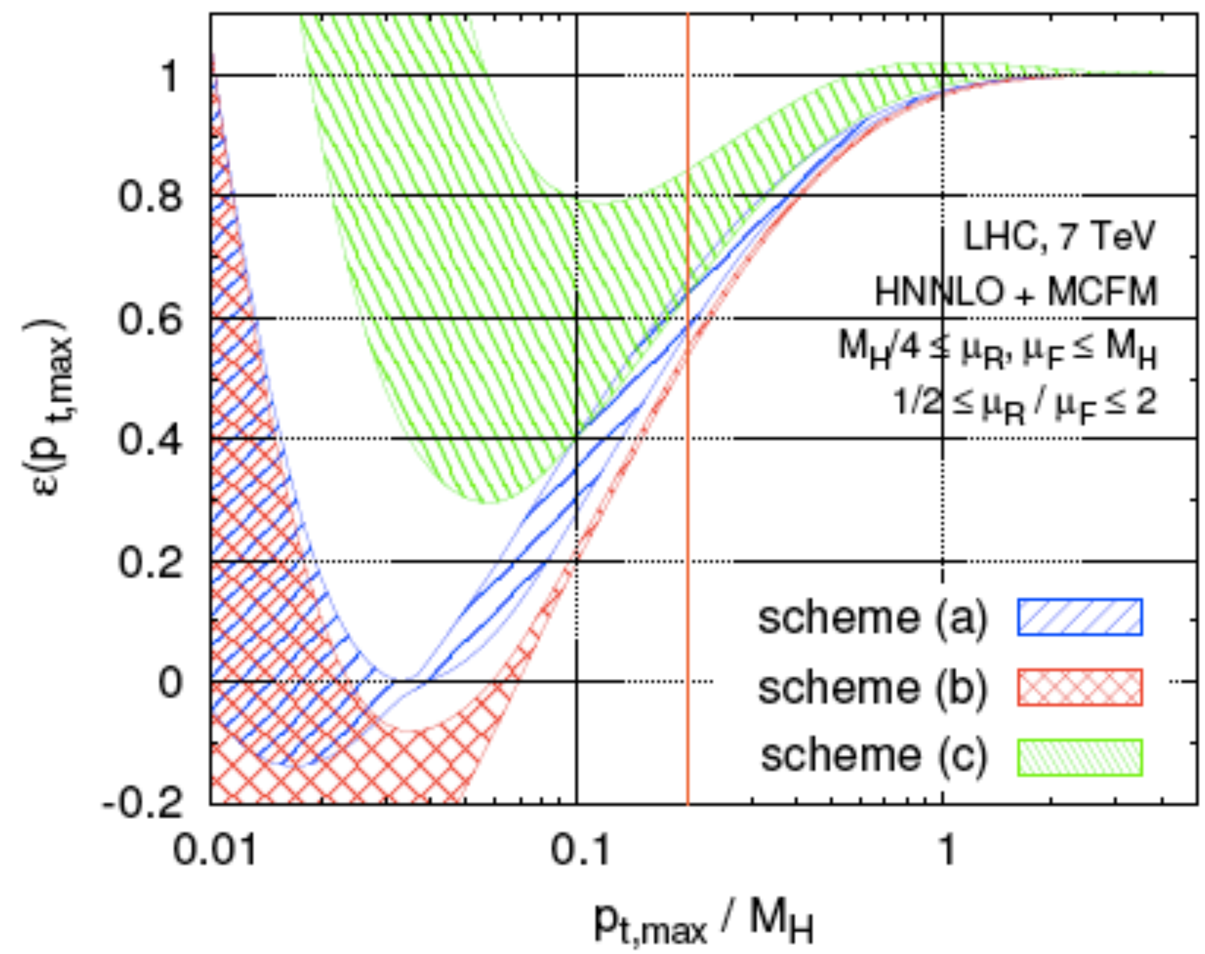
- Many issues in the description of Higgs with jets

Source (1-jet)	Signal (%)	Bkg. (%)
1-jet incl. ggF signal ren./fact. scale	26	-
2-jet incl. ggF signal ren./fact. scale	15	-
Parton shower/ U.E. model (signal only)	10	-
b-tagging efficiency	-	11
PDF model (signal only)	7	-
QCD scale (acceptance)	4	2
Jet energy scale and resolution	1	3
W+jets fake factor	-	5
WW theoretical model	-	3

J. Qian, ATLAS

Theory uncertainties becoming a limiting factor in many analyses, especially WW

$\sigma_0 = \sigma_{tot} - \sigma_{>=1}$



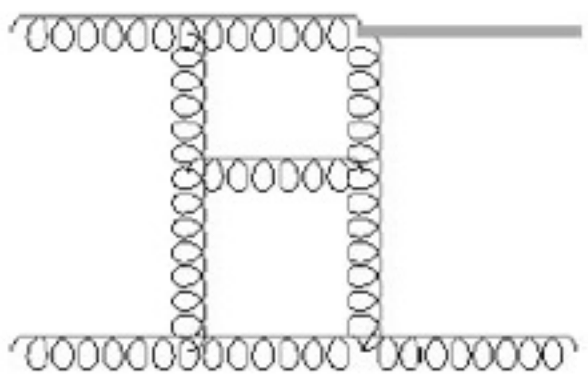
Banfi et al, 2012

Significant uncertainties exist when exclusive jet bins are used

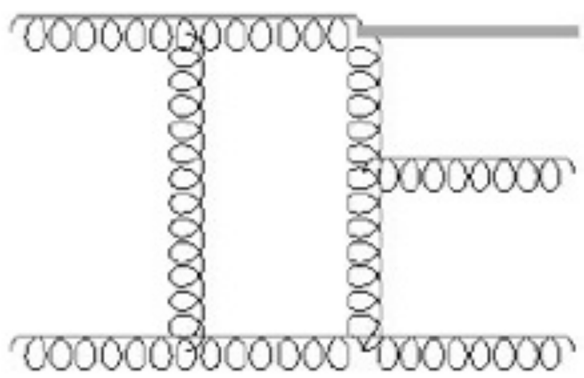
Urgently need NNLO for H+jets to resolve these issues

Structure of NNLO cross sections

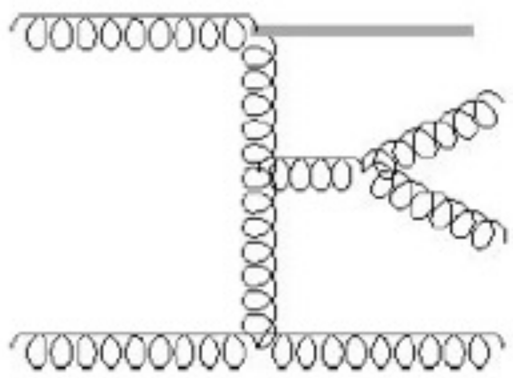
- Need the following ingredients for H+1j @ NNLO cross section



Gehrmann, Jaquier, Glover, Koukoutsakis (2011)



Badger, Glover, Mastrolia, Williams (2009)



Del Duca, Frizzo, Maltoni;
Dixon, Glover, Khoze (2004)

- All ingredients were available, some even for a while, what stopped us from having this calculation done before now?

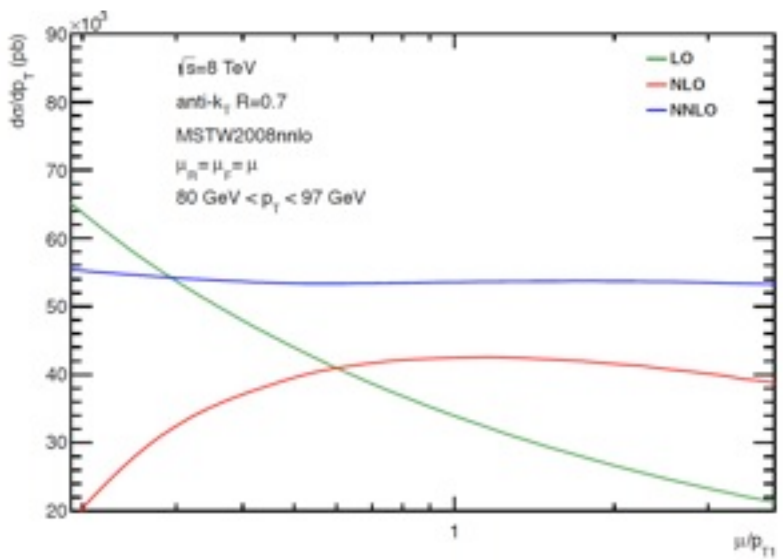
  - IR singularities cancel in the sum of real and virtual corrections and mass factorization counterterms but only after phase space integration for real radiations

  - Virtual corrections have explicit IR poles, whereas real corrections have implicit IR poles that need to be extracted.

  - Need a procedure to extract real radiation singularities before phase-space integration. This is a highly non-trivial task.

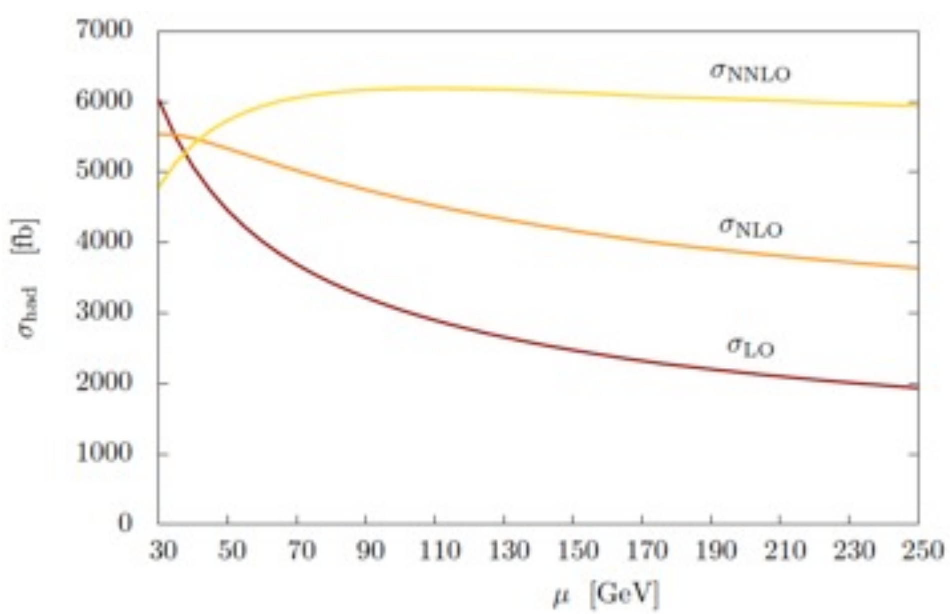
First NNLO QCD results to processes with both colored initial and final states

- After more than a decade of research we finally know how to generically handle NNLO QCD corrections to processes with both colored initial and final states



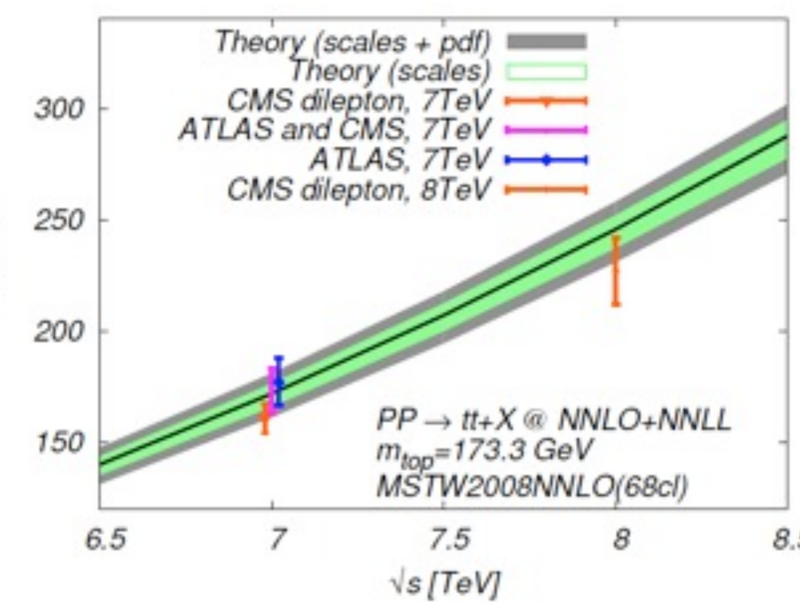
Gehrmann-de Ridder, Gehrmann, Glover, Pires (2013)

dijet: gg-channel



R.B., Caola, Melnikov, Petriello, Schulze (2013)

H+1j:gg-channel



Czakon, Fiedler, Mitov (2013)

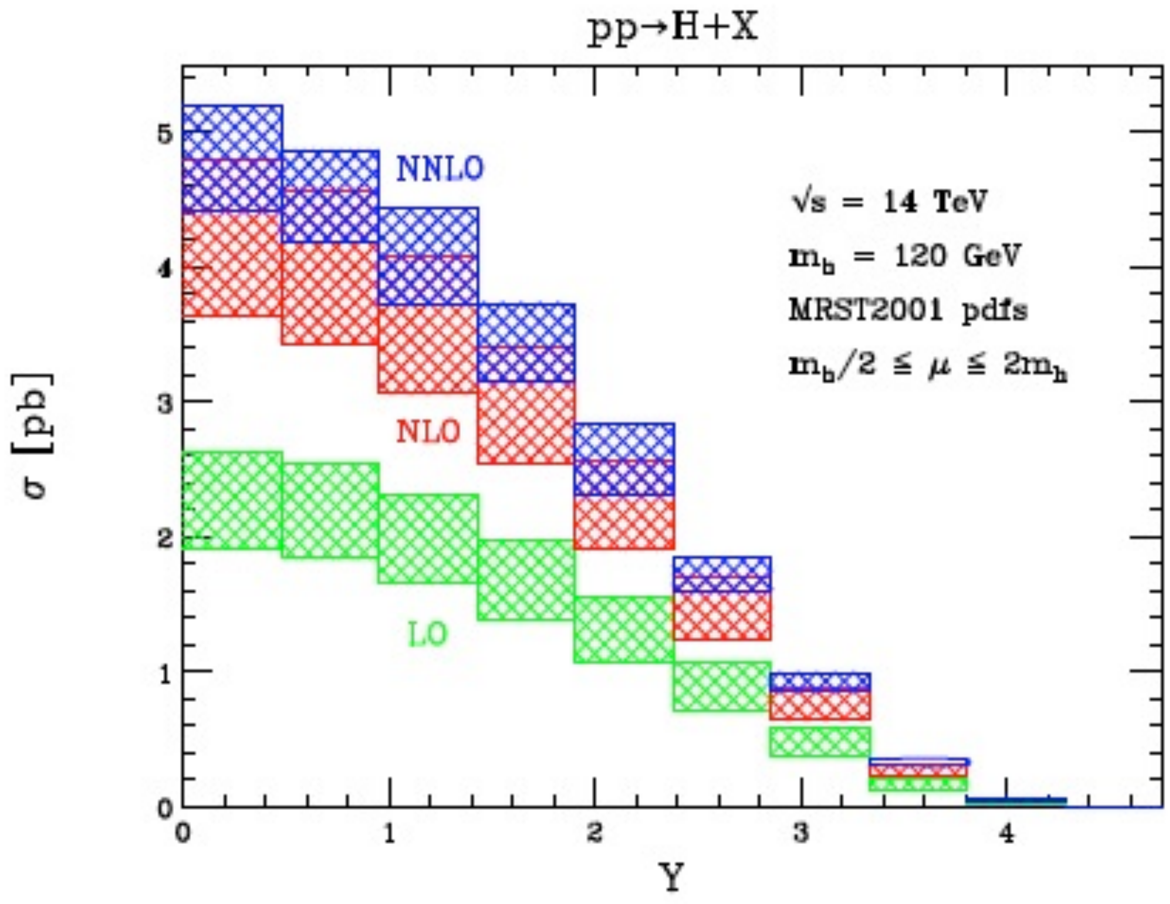
ttbar: all-channels

Based on Antenna subtraction scheme

Based on sector-improved subtraction scheme

Sector decomposition

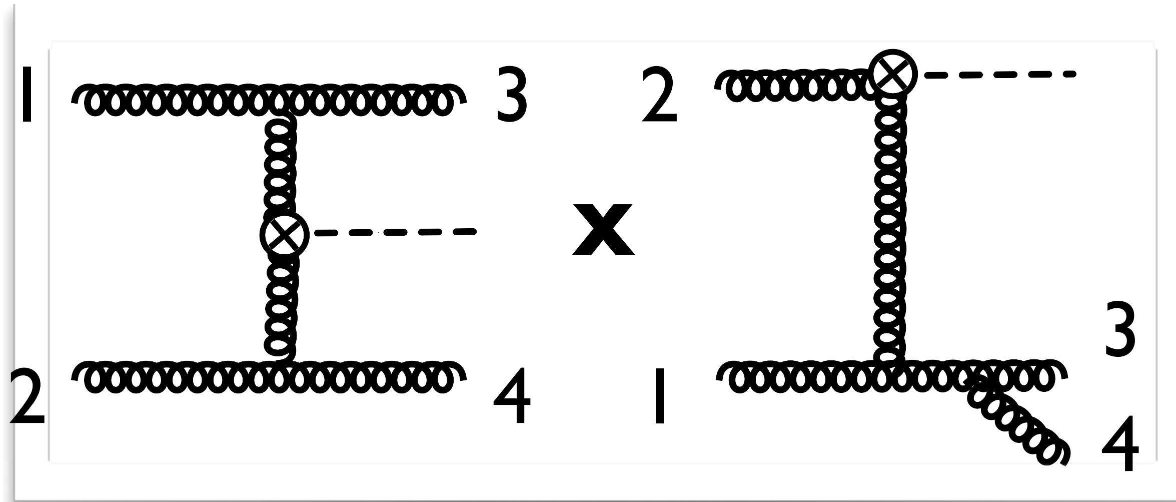
- One method successfully used in the past to obtain NNLO cross sections is sector decomposition Binoth, Heinrich; Anastasiou, Melnikov, Petriello (2003)
- Basic idea: introduce explicit parameterizations of phase space in which the poles in ε can be easily extracted via a plus-distribution expansion



- $e^+e^- \to 2$ jets
Anastasiou, Melnikov, Petriello (2004)
- Higgs production at hadron colliders
Anastasiou, Melnikov, Petriello (2005)
- Electroweak gauge boson production
Melnikov, Petriello (2006)

The downside

- To illustrate the drawbacks, use Higgs production as an example



- Invariants that occur in this topology : s_{13}, s_{24}, s_{134}, s_{34}. These contain the collinear singularities $p_1||p_3$, $p_2||p_4$, $p_3||p_4$, $p_1||p_3||p_4$

- Initial uses of sector decomposition attempted to find a ***global*** parameterization of phase space to handle all of these singularities at once

- However, can only have: p1||p3 & p2||p4 or p1||p3||p4. Not all invariants above can have collinear singularities simultaneously

- The attempt to find suitable global parameterizations meant that one would need to find an entirely new parameterization for Higgs+jet, since the additional final-state parton leads to new singularities; can't recycle information from differential Higgs production

Sector-improved subtraction scheme

- A combination of sector decomposition and FKS (Frixione,Kunszt,Signer) ideas makes the extraction of singularities more systematic Czakon (2010)

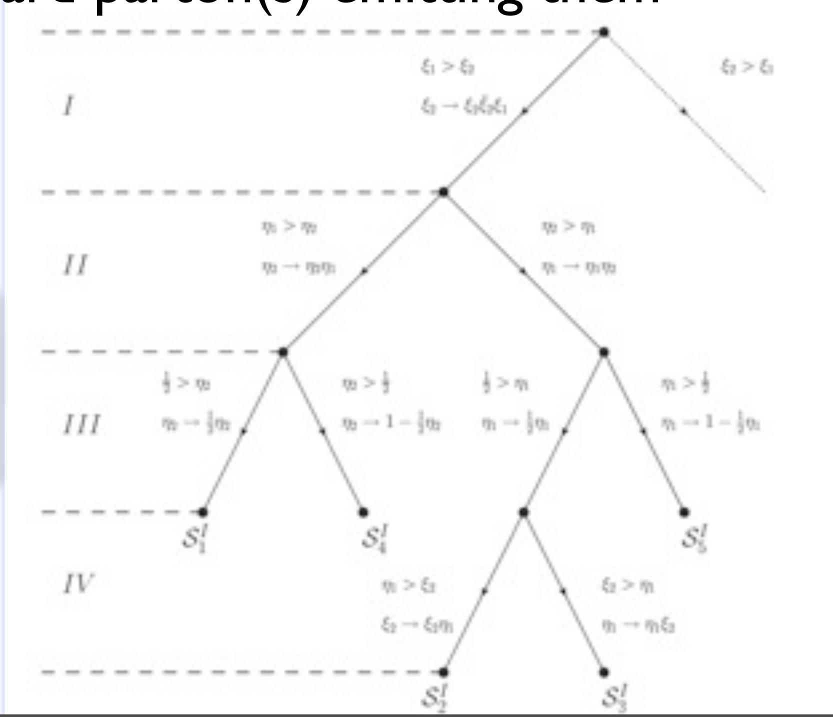
  - @ NNLO the elementary building block is the double unresolved phase space where two unresolved particles can become soft or collinear to one or two hard directions

  - partition the phase space such that in each partition only a subset of particles leads to singularities: only two soft singularities can occur, and only one triple collinear or one double collinear singularity can occur.

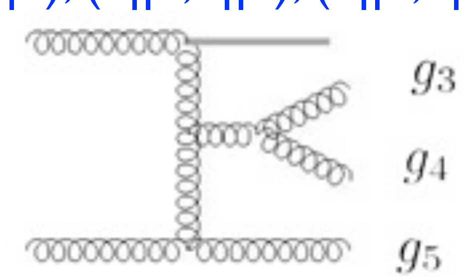
  - we can now pick a ***local*** parametrization for each partition

  - the partitioning is done using energies and angles of the unresolved particles w.r.t. the hard parton(s) emitting them

$\eta \sim$ angles
$\xi \sim$ energies



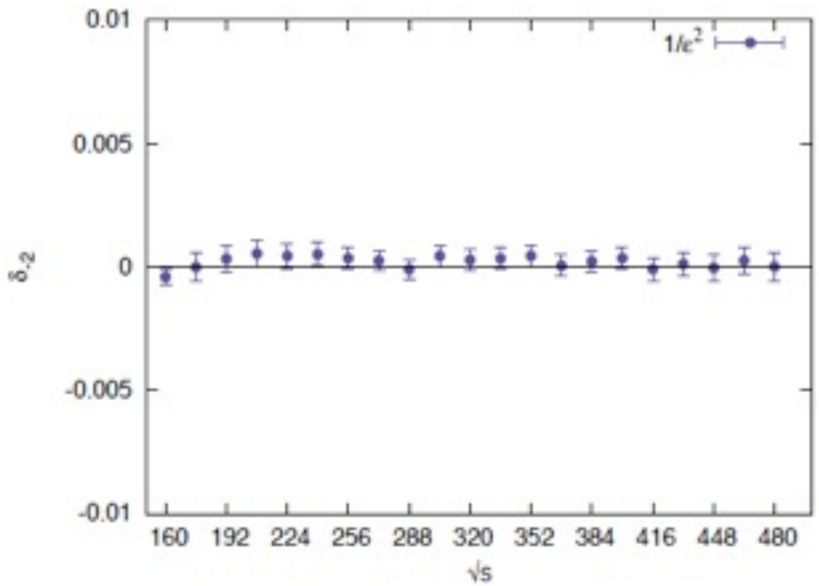
- disentangling singularities as energies and angles vanish leads to a tree of sectors.
- Need to consider the following partitions for H+1j:
  - triple collinear partitions: (5||4||1), (5||4||2) , (5||4||3) ;
  - double collinear partitions: (5||1,4||2), (5||1,4||3), (5||3,4||1), (5||3,4||2),(5||2,4||1),(5||2,4||3)

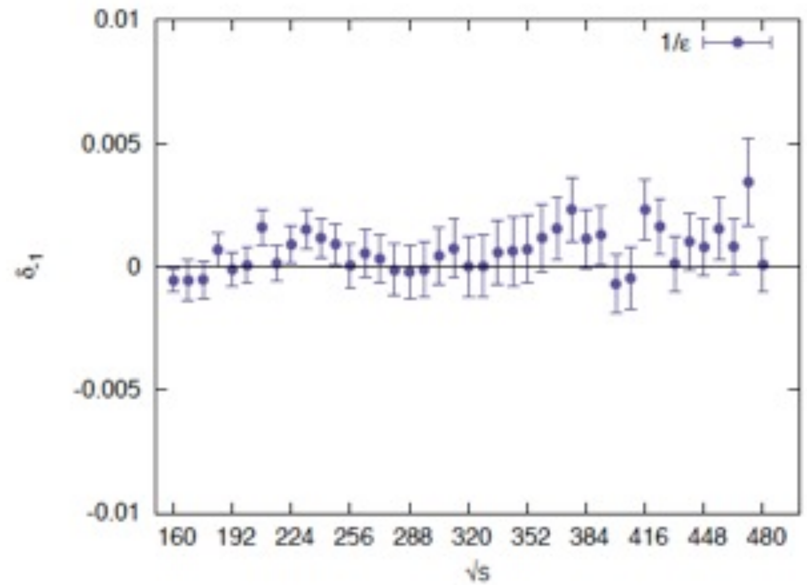


H+jet @ NNLO: gg-channel

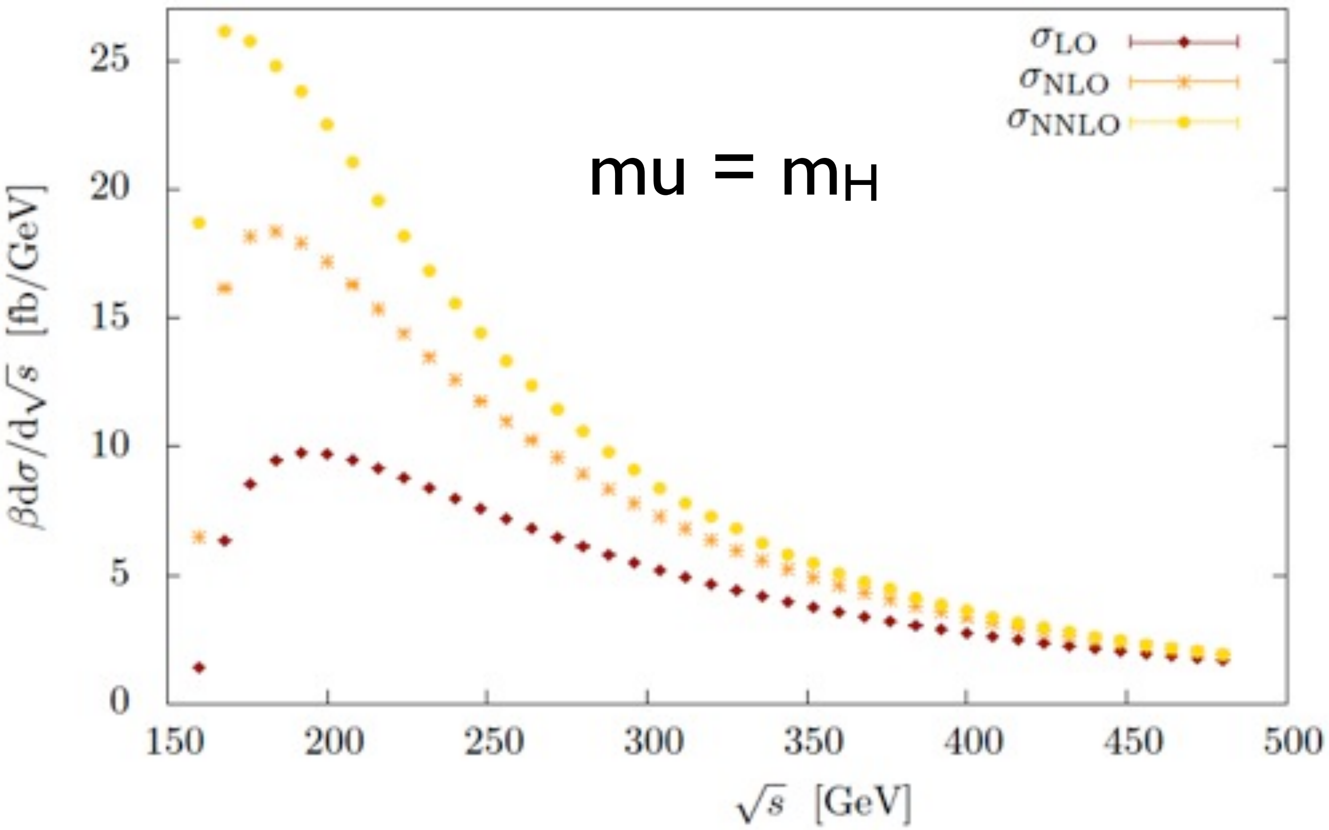
Checks:

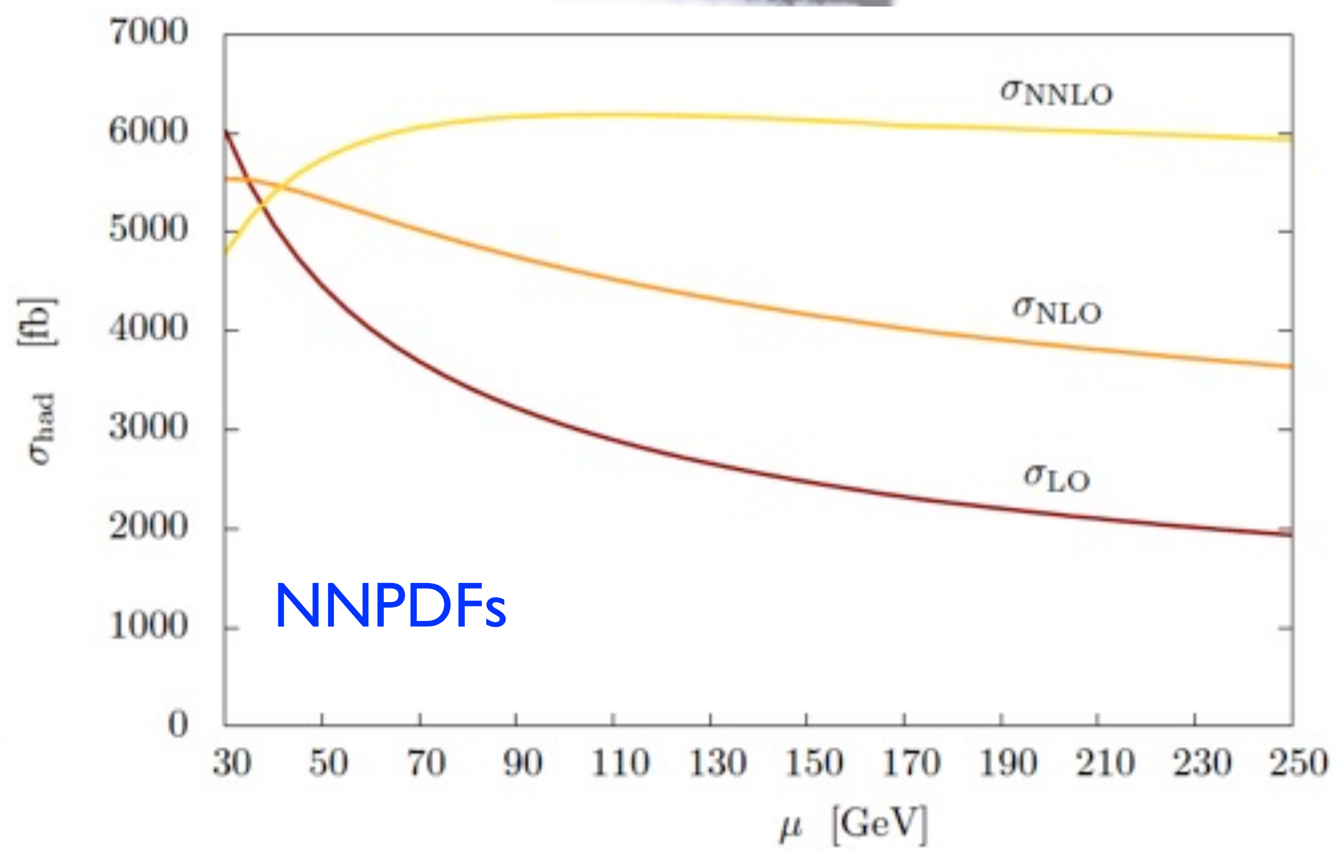
- Two separate calculations were performed and agreement was found on all the steps
- Correctness of the limits: the subtraction terms should approach the full amplitudes in the singular limit. Subtraction terms are constructed from reduced matrix elements using QCD factorization of soft and collinear singularities. This is a non-trivial check since the two contributions are calculated independently from each other.
- Numerical cancellation of poles. This is another non-trivial check since all the ingredients including renormalization and collinear subtraction contribute. A typical cancellation of poles is 10^{-4} for ep^{-2} and 10^{-3} for ep^{-1}.





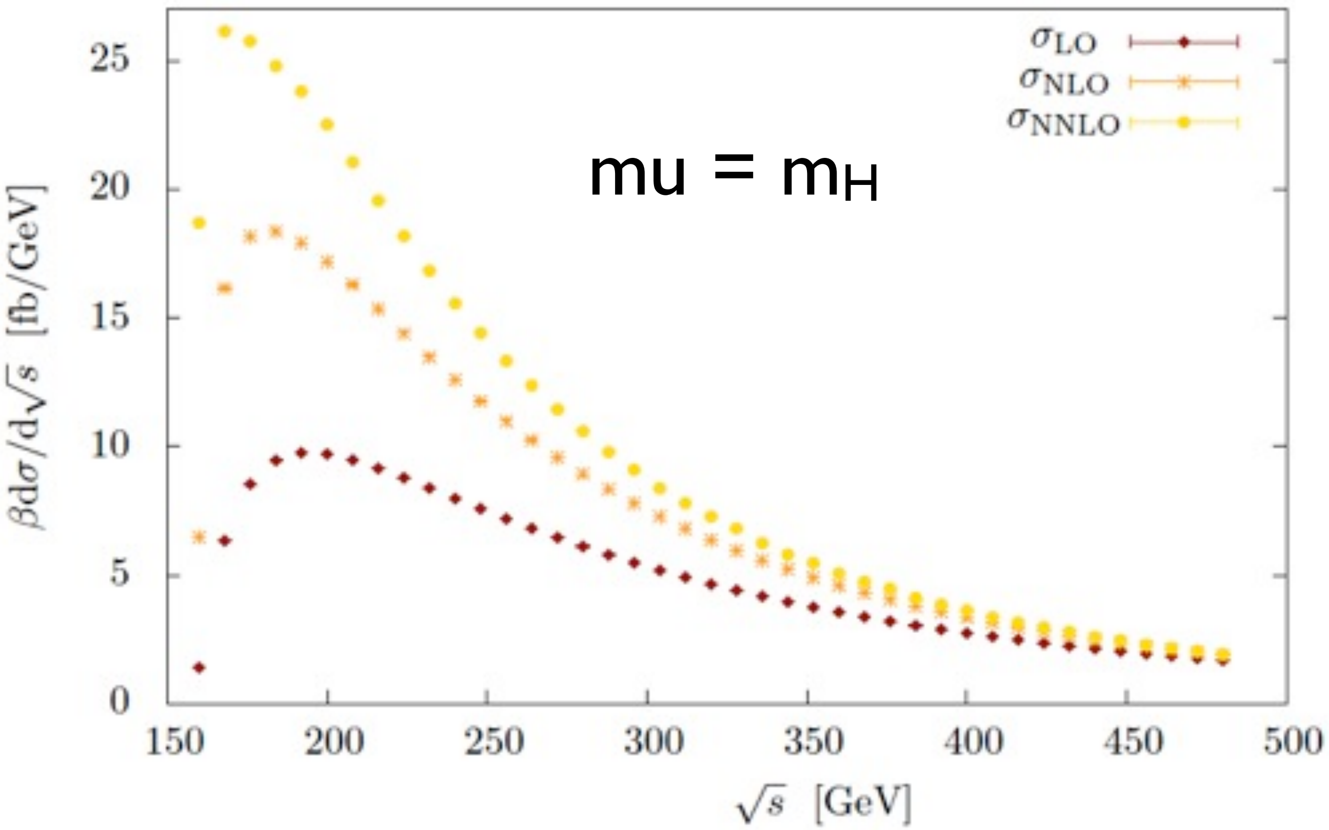
H+jet @ NNLO: gg-channel

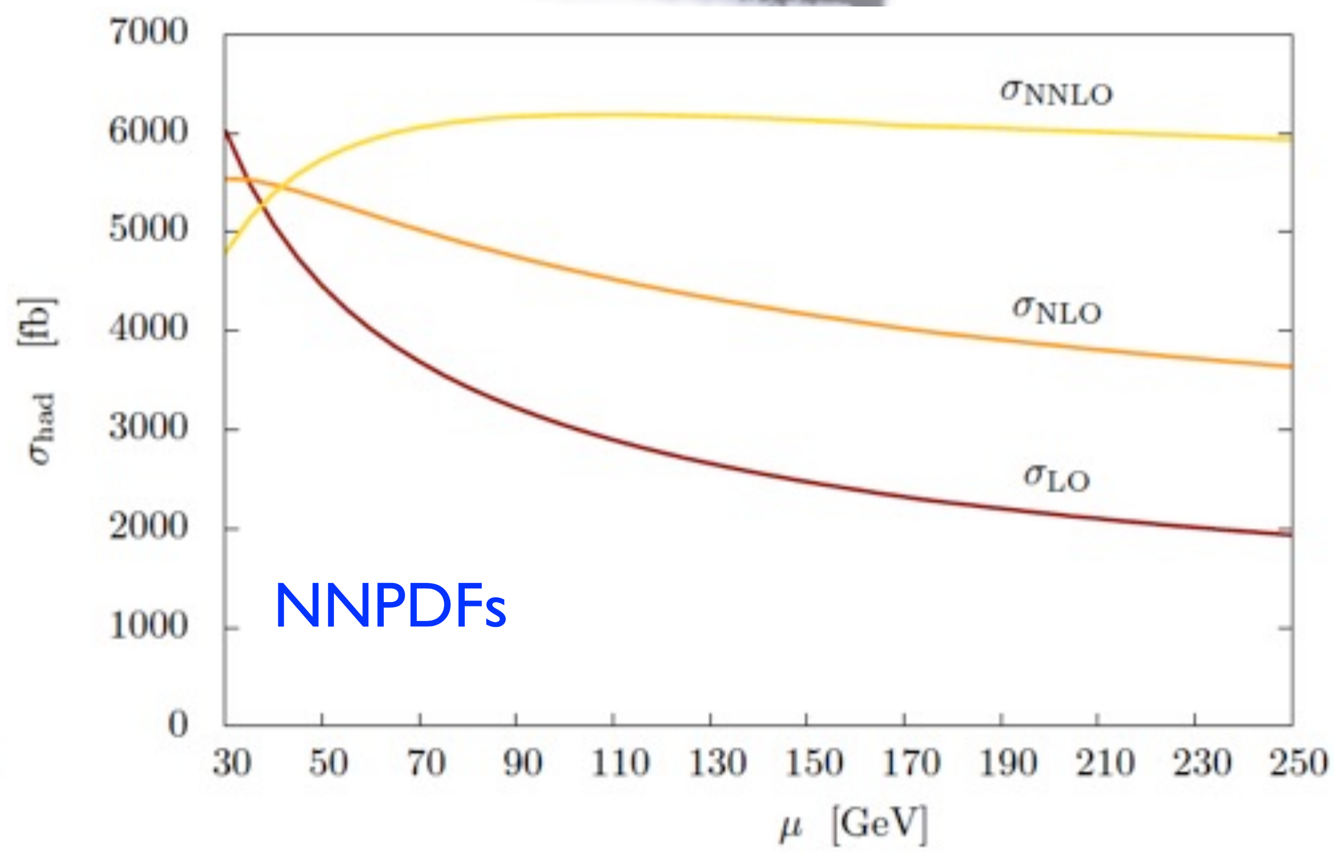




- We compute partonic cross sections for gg→H+jet at LO, NLO, NNLO in QCD
- We use the k_T-jet algorithm, P_{Tj} > 30GeV, R=0.4, mH=125GeV
- Hadronic cross sections for pp→H+jet at 8TeV LHC are produced by convoluting with PDFs. We present results using NNPDFs for the scale choices $m_H/2$, m_H, $2m_H$

H+jet @ NNLO: gg-channel





$$\sigma_{\mathrm{LO}}(pp \to Hj) = 2713^{+1216}_{-776}\ \mathrm{fb},$$
$$\sigma_{\mathrm{NLO}}(pp \to Hj) = 4377^{+760}_{-738}\ \mathrm{fb},$$
$$\sigma_{\mathrm{NNLO}}(pp \to Hj) = 6177^{-204}_{+242}\ \mathrm{fb}.$$

$\sigma_{NLO}/\sigma_{LO} = 1.6$

$\sigma_{NNLO}/\sigma_{NLO} = 1.3$

Summary

- We have moved beyond the discovery stage of the Higgs and have begun analyzing the discovered particle
- SM predictions for the Higgs are the benchmark against which all other possibilities will be compared
- Urgently need Higgs+jet at NNLO because of large theoretical systematic errors in the 1-jet bin, particularly in the WW channel
- First results for $gg \to H$+jet production at NNLO in QCD for realistic jet algorithms.
- We observe a large K factor, a 30% enhancement w.r.t. NLO for $mu=m_H$
- Significant reduction of scale dependence from 50% at LO to 20% at NLO to less than 5% at NNLO.